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The National Ignition Facility: Transition to a Target Shooter

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The National Ignition Facility: Transition to a Target Shooter (U)

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The National Ignition Facility (NIF), currently under construction at the Lawrence Livermore National Laboratory, is a stadium-sized facility containing a 192-beam, 1.8-Megajoule, 500-Terawatt, ultraviolet laser system together with a 10-meter diameter target chamber with room for nearly 100 experimental diagnostics. When completed, NIF will be the world's largest and most energetic laser experimental system, providing an international center to study inertial confinement fusion and the physics of matter at extreme energy densities and pressures. NIF's 192 energetic laser beams will compress fusion targets to conditions required for thermonuclear burn, liberating more energy than required to initiate the fusion reactions. Other NIF experiments will allow the study of physical processes at temperatures approaching 10^8 K and 10^{11} Bars, conditions that exist naturally only in the interior of stars, planets and in nuclear weapons. NIF is now entering the first phases of its laser commissioning program. This paper provides a detailed look the NIF laser systems and the results of recent laser commissioning shots. We discuss plans for experiments using the first laser beams of NIF and plans for future uses of NIF, including short pulse laser capability on NIF for high energy, high brightness radiographic x-ray backlighters for physics experiments of importance to the Stockpile Stewardship Program. (U)

Introduction

The National Ignition Facility (NIF) under construction at the Lawrence Livermore National Laboratory (LLNL) will be a center to study inertial confinement fusion and the physics of extreme energy densities and pressures. The building housing the laser system was completed in September 2001 and the construction of all 192 ultra-clean and precision aligned beam path enclosures was completed in September 2003. In late 2002 NIF began activating its first four laser beam lines and by July 2003 NIF had delivered world-record single laser energy performance in primary (1.06 micron infrared light), second, and third harmonic wavelengths. The first diagnostics capability has been installed and physics experiments have begun.

When completed in 2008, NIF will provide up to 192 energetic laser beams to compress deuterium-tritium fusion targets to conditions where they will ignite and experience thermonuclear burn, liberating more energy than is required to initiate the fusion reactions. NIF experiments will allow the study of physical processes at temperatures approaching 100 million K and 100 billion times atmospheric pressure. These conditions exist naturally only in the interior of stars and in nuclear weapons explosions *(Laboratory Microfusion Study, 1990; Krupke, 1995; Lindl, 1998; Tarter, 2002)*.

The NIF Laser System

The National Ignition Facility layout is shown in Figure 1. NIF consists of a number of sub-systems including amplifier power conditioning modules to drive large flashlamp arrays that power the neodymium-doped glass laser, the injection laser system consisting

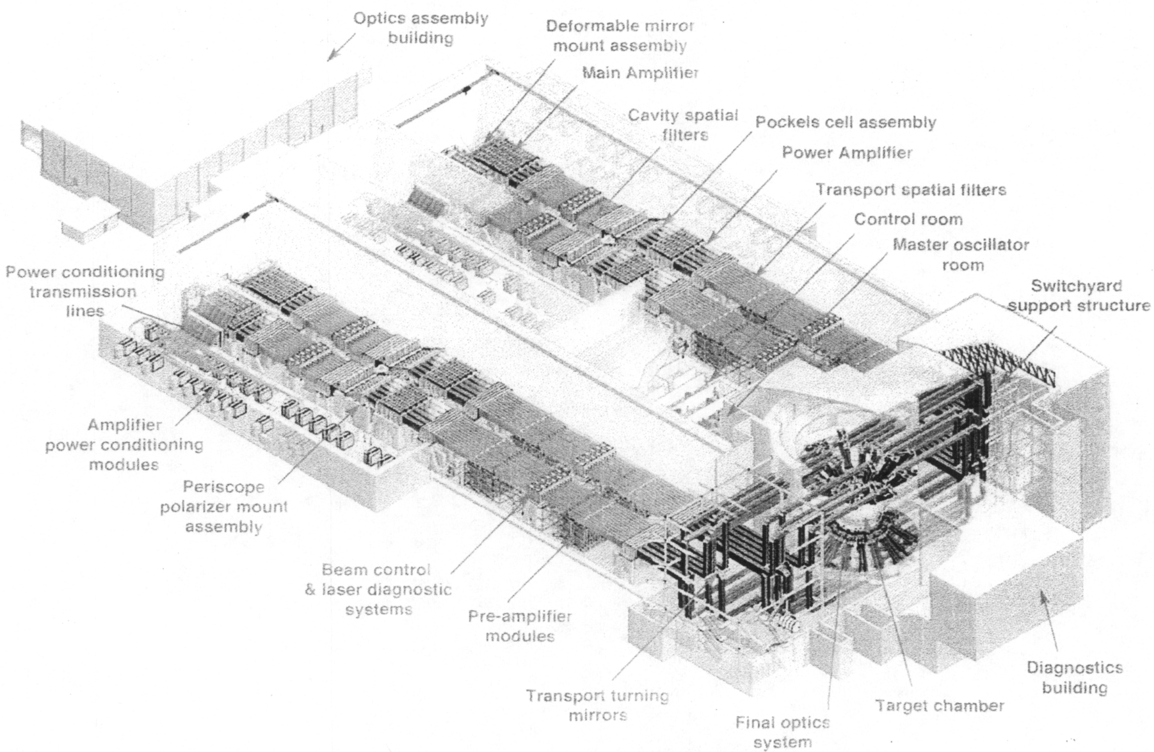

Fig. 1. Schematic view of the National Ignition Facility showing the main elements of the laser system. The 10-meter diameter target chamber sets the scale for the facility.

of the master oscillator and preamplifier modules, the main laser system along with its optical components, the switchyards, and the 10-meter diameter target chamber and its target experimental systems. The entire laser system, switchyards, and target area is housed in an environmentally controlled building. An integrated computer control system is located in the core of the facility to monitor, align, and operate the more than 60,000 control points required for NIF's operation. A 2,000 square meter cleanroom facility, the Optics Assembly Building, is located at one end of NIF for assembling and installing the precision optical and opto-mechanical components that make up the NIF laser system. On the opposite end of the facility the Diagnostics Building houses experimenters, a data acquisition system, and target preparation and storage areas.

The NIF laser system is comprised of 192 high-energy laser beams. For inertial confinement fusion studies the laser beams will produce a nominal 1.8 million joules (approximately 500 trillion watts of power for 3 nanoseconds) of ultraviolet laser energy onto a target. This is approximately 60 times the energy available in the Nova laser, which was operated at LLNL between 1983 and 1999, or the Omega Laser at the University of Rochester's Laboratory for Laser Energetics. NIF can provide a range of beam energies and powers for experimental and diagnostic x-ray backlighter applications.

NIF's architecture and operation have been described in detail elsewhere *(Moses et al., 2003; Newton, et al., 2003)*. NIF includes a single master oscillator with arbitrary waveform generation capability split into 48 pulses feeding a high-gain preamplifier system. Each preamplifier injects joule-level pulses into a "quad" of four beams in the main laser system. Each beam is approximately 40 cm x 40 cm in area. The main laser system consists of two stages of large flashlamp-pumped neodymium-doped glass amplifiers with multi-pass capability for both high gain and high energy extraction efficiency. Laser light is switched in and out of the main amplifier cavity using full aperture plasma-electrode Pockels cells and polarizers. Each laser beam utilizes a full-aperture adaptive optic deformable mirror to correct wavefront aberration. The total amplification factor for the 192-beam system is over 10^{15}. High-energy laser beams are transported in quads through argon-filled beam tubes to final optics assemblies located on the target chamber. Final optics convert the laser light to the third harmonic, focus the light to target chamber center and provide diagnostic sampling and debris protection.

Figure 2 shows one of the 192 laser beams, detailing the key elements of a NIF beamline, called line-replaceable units. All major laser components are assembled in clean, pre-aligned modules called line-replaceable units or LRUs. These LRUs contain laser optics, mirrors, lenses, and hardware such as pinhole filter assemblies that are robotically installed into NIF's beampath infrastructure, while maintaining the high level of cleanliness required for proper laser operation. Autonomous guided vehicles carrying portable clean rooms position themselves underneath NIF's beampath enclosures and robotically insert LRUs into the beampath. The installation, integration, and commissioning of the beampath infrastructure at the required cleanliness levels has been successfully accomplished for the more than 120 LRUs required for NIF's first four laser beam lines.

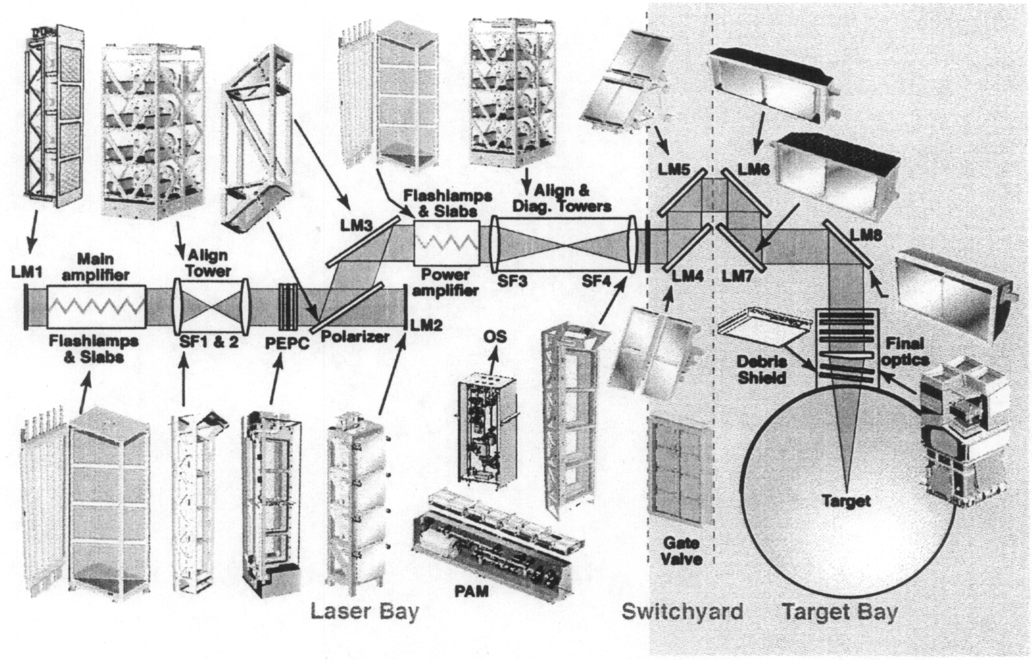

Fig. 2. Schematic representation of a NIF laser beam line showing the line-replaceable units in each line.

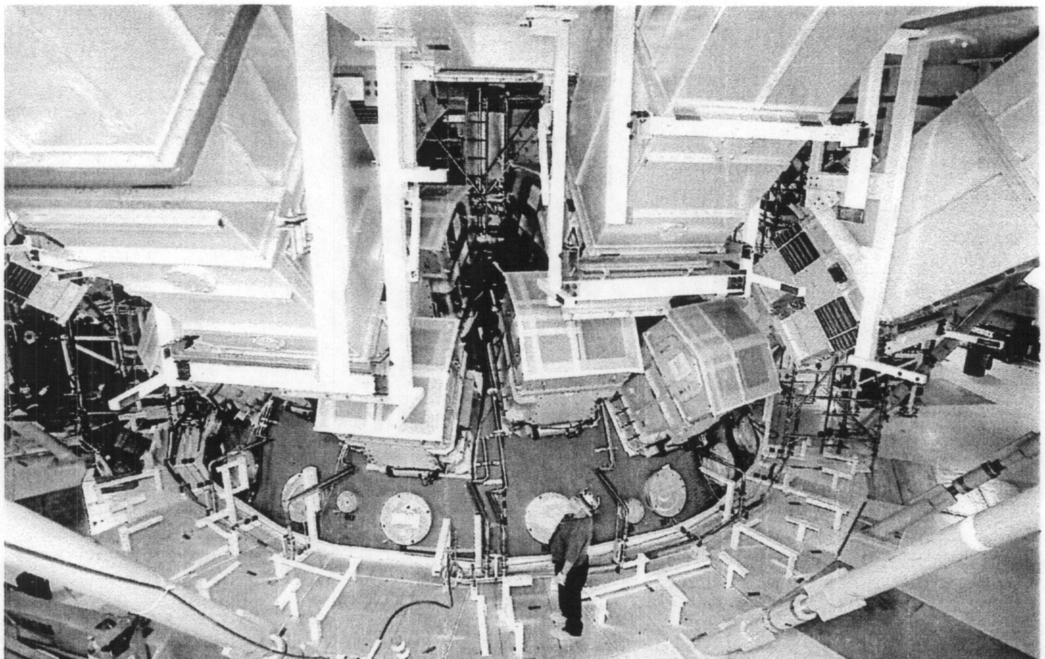

Fig. 3. Target chamber upper hemisphere showing 24 quads of beam tubes installed.

NIF's 10-meter diameter target chamber includes a number of laser entry ports that allow quads of four laser beams to be focused to the center of the target chamber through a final optics assembly (FOA). The FOA is a precision optical assembly containing optics to provide a variety of spatial beam profiles on target, KDP and deuterated KDP plates to convert the infrared laser light into the ultraviolet, the final focus lens, debris shields and vacuum gate valve for each beam.

NIF uses over 7,500 large optics, including glass slabs, KDP crystals, mirrors, windows, lenses, polarizers, and diffraction gratings. There are over 26,000 smaller optics used in the Injection Laser System *(Stolz et al., 2003; Moses et al., 2003).*

The NIF target chamber and final focusing system is designed with maximum flexibility for experimental users and includes120 diagnostic instrumentation and target insertion ports. During initial operation, NIF is configured to operate in the "indirect drive" configuration, which directs the laser beams into two cones in the upper and lower hemispheres of the target chamber. This configuration is optimized for illuminating the fusion capsule mounted inside cylindrical hohlraums using x-rays generated from the hot walls of the hohlraum to implode the capsule. NIF can also be configured into a more symmetrical "direct drive" arrangement of beams. Figure 3 shows a recent photograph of the upper half of the target chamber.

NIF Early Light

NIF construction began in May 1997 and nearly all192 beampath enclosures are now in place and ready for optics installation. Figure 4 shows the beampath installed in Laser Bay 2. In October 2001 the first laser light from NIF's master oscillator was generated in

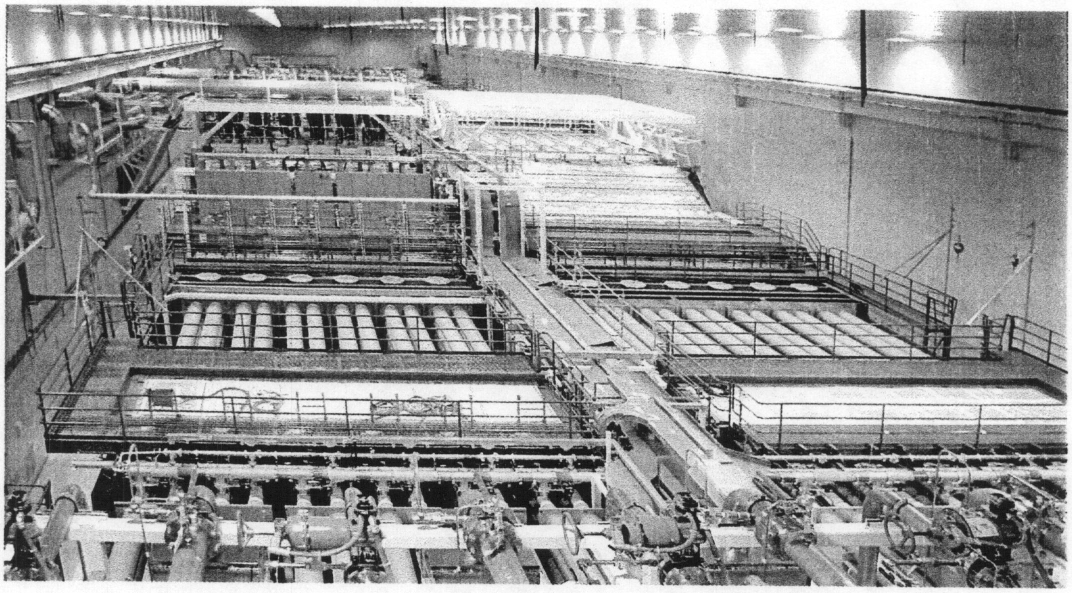

Fig. 4. The completed beampath for 96 laser beams in Laser Bay 2.

the master oscillator room located in the central core of the NIF building. This master oscillator has demonstrated the required pulse shaping stability and accuracy for high contrast ignition pulses and other types of laser pulses that are of interest to NIF experimenters. In June 2002 the first preamplifier module was installed in the Laser Bay and routinely amplifies master oscillator pulses to the joule level.

First high energy 3ω laser light to the center of NIF's target chamber was achieved in January 2003 with approximately 1 kilojoule (kJ) of laser energy focused onto a simple foil target. The energetic x-rays emitted from this target were measured with an x-ray pinhole imaging system called the Static X-ray Imager (SXI) mounted on the target chamber. In April 2003 10.6 kJ of 3ω light was produced in four beams and directed to a target in the target chamber. Recently we have delivered 16 kJ of 3ω light in four beams to the target chamber for experiments.

A separate target chamber, known as the Precision Diagnostic System (PDS) is used to fully characterize NIF's 1ω, 2ω, and 3ω laser beam energy, power, and wavefront to validate and enhance computer models that predict laser performance. Any one of the four NIF beams can be directed into the PDS using a robotic mirror and transport system. Figure 5 shows examples of high-energy 2ω and 3ω beams imaged in the near field using the PDS.

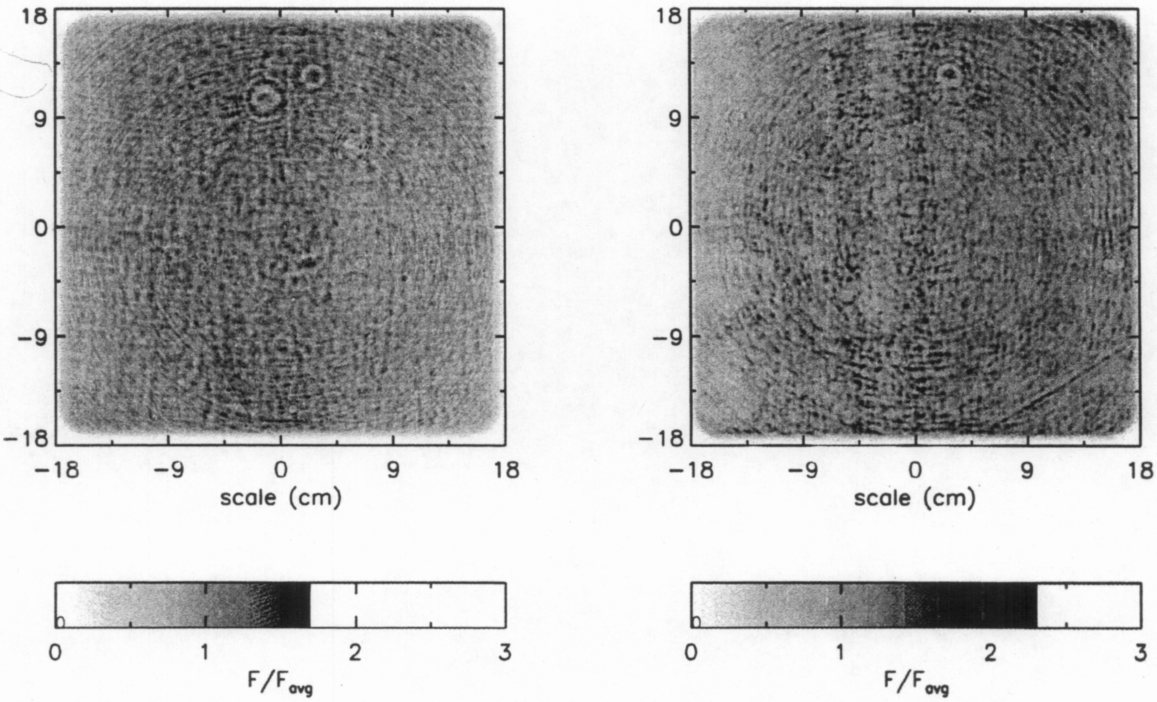

Fig. 5. Near field image of an 11.4 kJ 2ω and 10.4 kJ 3ω NIF beams showing excellent contrast uniformity, exceeding NIF's requirements.

At this time NIF's highest 3ω single laser beam energy is 10.4 kJ, equivalent to 2 MJ for a fully activated NIF, exceeding the NIF energy point design of 1.8 MJ. This energy was achieved with 13.65 kJ 1ω drive in a 3.5 ns pulse. We have also conducted a series of shots generating green or 2ω laser light with single beam energy up to 11.4 kJ in a 5 ns square pulse. This is equivalent to nearly 2.2 MJ on target for 192 beams. In July 2003, 26.5 kJ of 1ω light per beam was produced. This energy is 30% greater than the drive energy required for NIF. NIF has now demonstrated the highest energy 1ω, 2ω, and 3ω beamlines in the world.

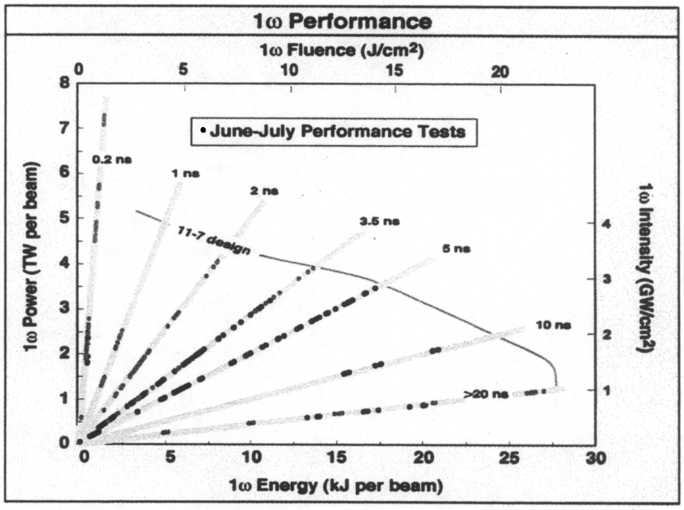

Fig. 6. 1ω energy vs. power is plotted for a number of NIF performance shots. The plot also indicates the level where energy and power is limited by the available number of glass slabs in the main amplifier (11 slabs) and the power amplifier (7 slabs).

High power campaigns have also been completed with drive power reaching 7 terawatts or about 5 gigawatts/cm^2. Figure 6 details energy and power achieved on a number of 1ω shots conducted through July 2003.

Beam-to-beam synchronization has been measured and adjusted to better than 6 picoseconds, which corresponds to approximately 1 part in 150,000 of the total beampath in NIF. Figure 7 shows this measurement using an x-ray streak camera diagnostic demonstrating NIF's timing performance. Complex shaped ignition pulses as well as ramped and flat-in-time pulses with multi-kJ energies and pulse lengths up to 25 ns have also been demonstrated.

Conclusions and Future Directions

The National Ignition Facility extends the experimental regimes of accessible high-energy-density (HED) by a significant amount compared to other current and planned high-energy laser and pulsed power facilities. Figure 8 shows one measure of NIF's physics reach for pressure versus pulse length. NIF, and the French Laser Megajoule (LMJ) system (recently approved for construction) can drive materials to tens of gigabars for tens of nanoseconds. NIF is capable of providing a range pulse lengths that under certain configurations can be hundreds of nanoseconds. The ability to deliver extended high-energy drive allows experimental measurements of equation of state (EOS),

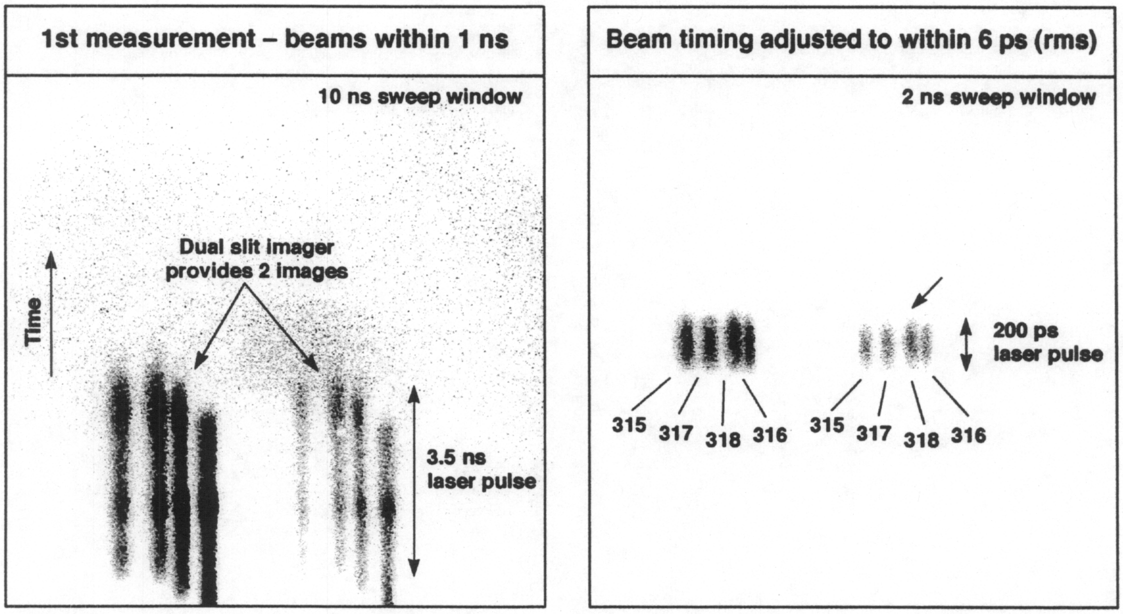

Fig. 7. Streaked x-ray images showing the beam-to-beam timing for a quad of four laser beams. Each image shows x-rays emitted from a target illuminated by the quad of beams and imaged through two different thickness filters.

materials at high pressures, hydrodynamics, and radiation transport that have not been possible in prior HED facilities.

Hohlraums driven with green or 2ω light from NIF are actively being studied *(Suter, 2003)*. Calculations suggest that as much as 1.5 MJ of energy may couple to a capsule at 250 eV drive temperature. However, physical data on 2ω laser plasma interactions is limited and more work is needed. NIF 2ω operation has been demonstrated and researchers are studying how to configure some of NIF's early beams for high-energy 2ω LPI studies.

In addition, we have begun

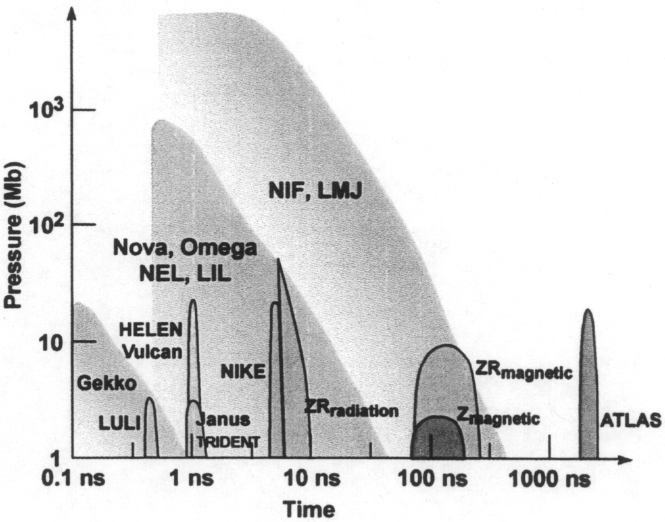

Fig. 8. Pressure-pulse length regimes accessible at different HED facilities currently operating or planned in the world. NEL and LIL refer to NIF Early Light (4 beams) and Ligne d'Intégration Laser, the LMJ 8-beam prototype.

looking at the design and deployment of high energy petawatt (HEPW) beam lines on NIF for high-energy-density science applications. NIF's current injection laser, main amplifier, and beam transport system could be modified to allow up to 20 high energy petawatt-class (HEPW) beams to be directed to target chamber center. Initial experiments are being designed to utilize a single kilojoule-class HEPW beam line with 1-30 picosecond pulse width to drive electron or proton cone-focused ignition. NIF long pulse beams totaling 250 kJ into a hohlraum with 8-fold, 2-cone symmetry (8 quads of 4 beams in opposite laser entrance holes) would be used to compress the capsule. This capability on NIF could be in place in the 2006 time frame.25 Additional HEPW beams in a quad could be installed to provide multi-kilojoule capability *(Barty, et al., 2003).*
Beam deployment on NIF supports experiments with steadily increasing capability, shown in Figure 9. The increasing symmetry and energy available enables a variety of target configurations including planar targets, horizontal and vertical half-hohlraums (halfraums), and vertical hohlraums with 4- and 8-fold symmetry that provides approximately 300 shots per year through 2008 for high-energy-density physics, inertial confinement fusion, and basic science. After project completion in 2008, NIF is expected to provide 700 shots per year as a national user facility. The first physics experiments are already being performed on NIF *(Glenzer, et al., 2003).* Initial experiments are studying laser-plasma interactions and hydrodynamics of shocked materials. In the coming year this unique facility will already be providing the first glimpses of conditions heretofore only found in the most extreme environments. This will be done under repeatable and well-characterized laboratory conditions for the benefit of basic and applied science.

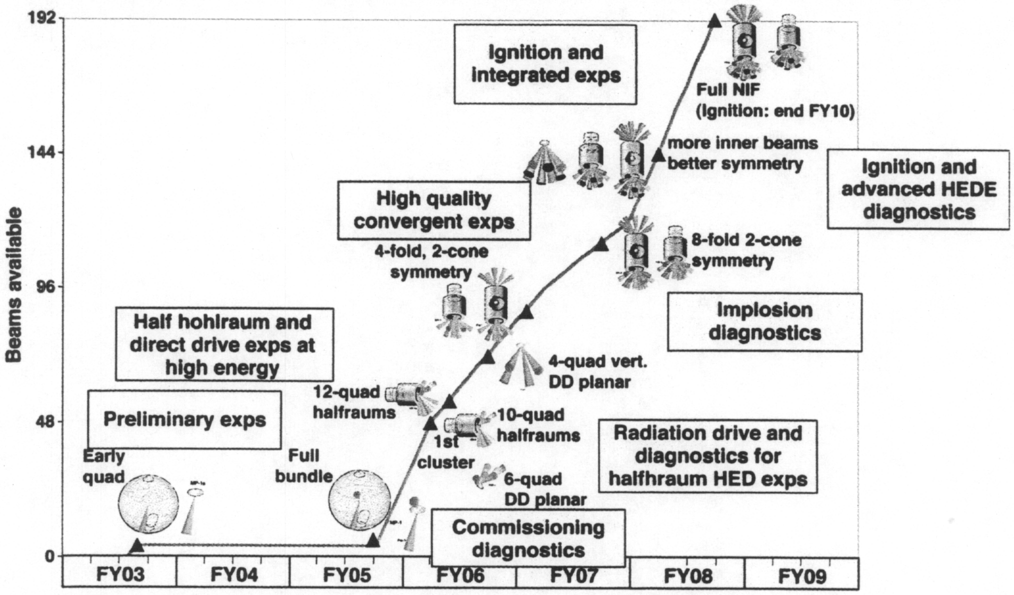

Fig. 9. The plan for completion of NIF provides increasing experimental capability over time for both experimental configurations and specialized diagnostics as more beams and symmetries become available.

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References

"Laboratory Microfusion Capability Phase-II Study," prepared by Interscience, Inc. for the Inertial Fusion Division Office of Research and Advanced Technology, ISI-TM9005281, May 31, 1990.

Krupke, W. F., ed., "Solid State Lasers for Application to Inertial Confinement Fusion (ICF)," Proc. SPIE 2633 (1995).

Lindl, J. , Inertial Confinement Fusion: The Quest for Ignition and Energy Gain Using Indirect Drive, Springer-Verlag (1998).

Tarter, C. B., "Inertial Fusion and Higher Energy Density Science in the United States," Proc. 2001 Conf. On Inertial Fusion Science and Applications (IFSA 2001), K. A. Tanaka, D. D. Meyerhofer, J. Meyer-ter-Vehn, eds., Elsevier (2002).

Moses, E. I. et al., "The National Ignition Facility: Status and Plans for Laser Fusion and High-Energy-Density Experimental Studies," Fusion Science and Technology, V. 43, p. 420, May 2003.

Newton, M. A. et al., "Initial Activation and Operation of the Power Conditioning System for the National Ignition Facility," Proceedings of the International Pulsed Power Conference 2003, Dallas, TX, June 15-18, 2003.

Stolz, C. J. et al., "Fabrication of meter-scale laser resistant mirrors for the National Ignition Facility, a fusion laser," submitted to the SPIE Proceddings of the International Symposium on Optical Science and Technology, Advances in Mirror Technology for X-ray, EUV Lithography, Laser, and Other Applications, 2003.

Moses, E. I. et al., "The National Ignition Facility: The World's Largest Optics and Laser System," UCRL-151593-JC, submitted for publication in the SPIE Proc. Of Photonics West, January 2003.

Suter, L. J., "Prospects for High-gain, High-yield NIF Targets Driven by 2w Light, Proceedings of the Third International Conference on Inertial Fusion Sciences and Applications, Monterey, CA, September (2003).

Barty, C. P. J. et al., Technical Challenges and Motivations for High Energy Petawatt Lasers on NIF, Proceedings of the Third International Conference on Inertial Fusion Sciences and Applications, Monterey, CA, September (2003).

Glenzer, S. et al., Progress in Long Scale Length Laser Plasma Interactions, Proceedings of the Third International Conference on Inertial Fusion Sciences and Applications, Monterey, CA, September (2003).